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## 13. ABSTRACT (Maximum 200 words)

The Staib Instruments EK-15-R RHEED System purchased on this DURIP grant has been mounted in the University of New Mexico's (UNM) Vacuum Generators VH80 MBE system and used extensively for RHEED studies during the growth of antimony-bearing semiconductors. The beam rocking feature in this unit has been critical in establishing the exact angle of incidence needed for clear observation of reconstruction patterns during the growth of bulk and digital alloy materials, and for the observation of RHEED oscillations to determine the precise growth rate. Observation of RHEED reconstruction patterns is particularly crucial in the growth of digital alloy (DA) materials. Arsenic-free GaInSb quantum well lasers for 2-5  $\mu\text{m}$  applications were fabricated by growing a graded digital alloy AlInSb metamorphic buffer layer on GaSb to tailor the lattice constant. The relaxation of the AlInSb DA buffer layer generates dislocations that are turned along the slip plane at strained heterojunctions. By increasing the number of heterojunctions, filtering of dislocations is possible. Below 200K the laser threshold was virtually constant, and a characteristic temperature  $T_0$  of 107K was found above 200K. This is the highest reported  $T_0$  for a semiconductor laser at this wavelength.

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# **Advanced RHEED Instrumentation for the Analysis of the Initial Stages of MBE Quantum Dot Growth for Semiconductor Lasers**

## **Final Report**

**Summary statement:** The Staib Instruments EK-15-R RHEED System purchased on this DURIP grant has been mounted in the University of New Mexico's (UNM) Vacuum Generators VH80 MBE system and used extensively for RHEED studies during the growth of antimony-bearing semiconductors. The beam rocking feature in this unit has been critical in establishing the exact angle of incidence needed for clear observation of reconstruction patterns during the growth of bulk and digital alloy materials, and for the observation of RHEED oscillations to determine the precise growth rate. Observation of RHEED reconstruction patterns is particularly crucial in the growth of digital alloy (DA) materials. The individual layers of which the DA are composed each have very different optimum growth conditions and rapid steering of the electron beam (using the rocking beam feature) allows optimization of the RHEED pattern on a time scale compatible with the growth of these thin layers. Such capability enables an evaluation of whether satisfactory growth conditions exist for all constituents of the DA.

The Horizontal Manipulator purchased from VG Semicon has not been installed due to an error in the original manufacture, which required replacement of the entire unit. Due to an error on the supplier's part, the unit supplied was built to mirror image specifications, which made it impossible to install in the MBE chamber for which it is intended. The unit could not be modified in the field, and a new unit was manufactured. Due to shortages in available materials, especially high purity refractory metals, the replacement unit was delayed and has arrived only in July 2001. It will be installed as soon as the MBE growth schedule permits. With this new horizontal manipulator we expect a more stable substrate platform, which will enable even greater precision in the alignment of the electron beam, with concurrent increase in the sensitivity of the RHEED reconstruction patterns.

The following description demonstrates the materials and laser capability that UNM now has with this new RHEED equipment

## **Background**

There is a need for antimonide-based, room-temperature, mid-infrared semiconductor lasers in the 2-5  $\mu\text{m}$  band with applications in chemical sensing, countermeasures, and laser radar. Typically arsenic is added to GaInSb to extend the emission wavelength of Type I quantum well active regions for mid-IR lasers fabricated on GaSb. Most notably, highly strained, electrically injected, InGaAsSb Type-I quantum well (QW) lasers with large arsenic content have been reported with wavelengths to 2.78  $\mu\text{m}$  [2]. With increased wavelength in this materials system, however, comes a loss in efficiency and degradation in the characteristic temperature,  $T_0$ . As a remedy, Type-II heterojunctions can provide longer wavelength lasers, but these structures suffer from small spatial overlap of the electron and hole wave-function[3]. The wave-function spatial overlap and the heavy-hole splitting can be increased by growing more complex Type-II wells such as the 'W' laser. These devices have shown strong optically-pumped performance [4] but still suffer from poor electrical characteristics [5]. Improved performance is expected by growing quaternary AlInGaAsSb alloys in the miscibility gap [6] and complex Type-II quantum wells where arsenic and antimony competition [7] makes repeatability an issue.

Arsenic-free GaInSb QW lasers for 2-5  $\mu\text{m}$  applications are realized by growing a graded AlInSb metamorphic buffer layer on GaSb to tailor the lattice constant. This approach maintains larger valence band offsets than adding arsenic to the active region making high performance Type I long wavelength lasers possible. The relaxation of the AlInSb buffer layer generates dislocations that are turned along the slip plane at strained heterojunctions. By increasing the number of heterojunctions, filtering of dislocations is possible. We have found that the filtering is optimally accomplished by fabricating the AlInSb buffer layer from a digital alloy that is step-graded to the desired lattice constant. Using this growth method, strong 300K photoluminescence has been observed at 2.5, 2.7, and 3.3  $\mu\text{m}$  indicating high quality active regions.

Figure 1 shows the optically pumped results for two samples with room-temperature target wavelengths of 2.5 and 2.7. The wafers are composed of 4 compressively-strained QWs sandwiched in a 1- $\mu\text{m}$  AlGaInSb waveguide region. The samples were cleaved into 1-mm cavity lengths and pumped with 222- $\mu\text{m}$  stripe widths. The pump is a 980 nm array using 50  $\mu\text{s}$  pulses and 5% duty cycle. The 2.5  $\mu\text{m}$  wavelength sample is composed of 100  $\text{\AA}$   $\text{Ga}_{0.60}\text{In}_{0.40}\text{Sb}$  wells with  $\text{Al}_{0.20}\text{Ga}_{0.48}\text{In}_{0.32}\text{Sb}$  barriers grown on a metamorphic buffer step-graded to  $\text{Al}_{0.73}\text{In}_{0.27}\text{Sb}$ . Room temperature operation was achieved with 15% differential quantum efficiency and 426  $\text{W}/\text{cm}^2$  threshold. The second sample is composed of 100  $\text{\AA}$   $\text{Ga}_{0.50}\text{In}_{0.50}\text{Sb}$  wells with  $\text{Al}_{0.20}\text{Ga}_{0.41}\text{In}_{0.39}\text{Sb}$  barriers grown on a metamorphic buffer step-graded to  $\text{Al}_{0.64}\text{In}_{0.36}\text{Sb}$ . 2.8  $\mu\text{m}$  room-temperature lasing was achieved with 28% differential quantum efficiency and 360  $\text{W}/\text{cm}^2$  threshold. Figure 2 shows the threshold power density versus temperature measurements between 100K and 320K for the second sample. Below 200K the threshold was virtually constant, and a characteristic temperature  $T_0$  of 107K was found above 200K. This is the highest reported  $T_0$  for a semiconductor laser at this wavelength.

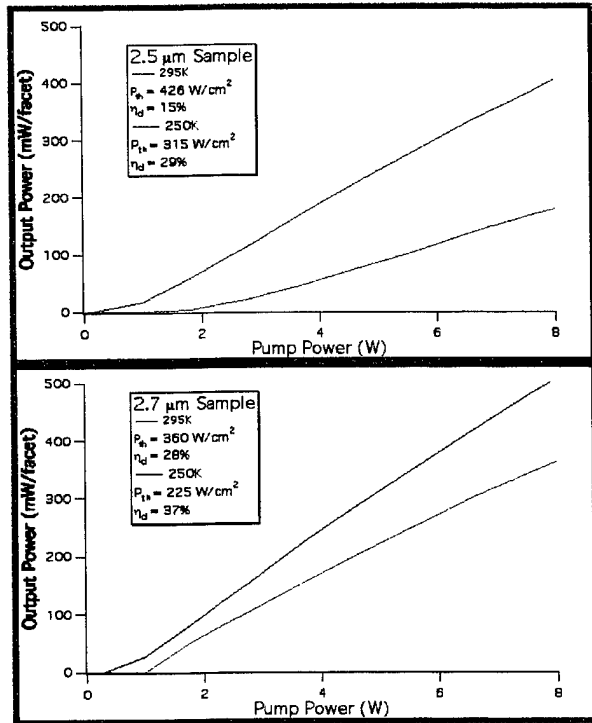


Fig. 1. Optically pumped results.

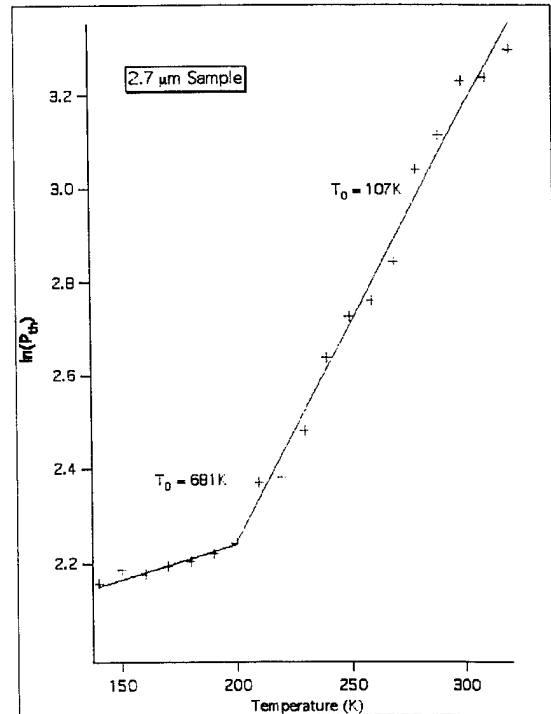


Fig. 2. Power Threshold measurements.

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